EXPERIMENTAL COMPARISON OF METHODS OF GENERATING HOT PLASMAS

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EXPERIMENTAL COMPARISON OF METHODS

OF GENERATING HOT PLASMAS

by

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FOREWORD

In order to begin a study of magnetohydrodynamic (MHD) effects in high temperature gases, it was decided to develop a plasma torch as a generator of the required high temperature gases. A device was needed that could operate reliably for at least several minutes and generate adequate volumes of hot gases (about $3000^{\circ}K$). Current commercial devices were beyond the financial capabilities of this study, so an attempt was made to develop such a device at RPI. A working model of the DC plasma torch was put in operation in the spring of 1960.

The author was to continue this study into MHD effects, but after some review, it was decided that the scope of even a simple MHD device was beyond the Master's level at this time. Early in 1961, information was obtained describing a plasma torch using radio frequency excitation and providing a very low level of contamination of the gases in the active part of the torch. It was felt that such a device might be a more valuable laboratory type generator than the DC plasma torch. Having almost no information on the operation of such a device, it was decided to construct one and determine whether or not it was feasible to use this mode of generation, or for that matter, which type (DC or RF torch) would best aid the original study.

The thesis is arranged basically into two sections. The first part attempts to give a rough idea of the wide range of interest in plasma generators. Many of these areas are far afield from the original study, but much important work is being carried on in them and a "broad brush treatment" of each area is necessary to give

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the reader an appreciation of the scope of this single project. The second part of the thesis attempts to answer the previous question or at least to indicate if further study into this comparison of generators is worthwhile.

The author wishes to express his appreciation to Dr. E. J. Holt, his thesis advisor, for the guidance, assistance and criticism which lead to this document; to Dr. W. R. Beam, Head of the Department of Electrical Engineering and Dr. L. P. Winsor, who were instrumental in the author choosing this thesis area and getting started therein; to Dr. E. F. Nippes and Dr. W. J. Childs for the use of the Metallurgy Department Laboratory and equipment; and to Mr. J. Wells of the Department of Electrical Engineering for his fine machine work in constructing and repairing the equipment used herein.

ABSTRACT

The specific problem in this investigation is to make a comparison of the operating characteristics of two types of plasma jets or torches. One type (DC plasma torch) uses conduction currents and the other (RF plasma torch) uses induction currents as the principle energy source for operation. The DC device has been a common source for high energy gases, but the RF device is very recent, first appearing in the literature in 1960.

Each device is described in detail and from graphs of operating characteristics, optimum parameters are found for the device described. The physical size of the device is not changed, but each device is optimized for the variable parameters of gas flow and power input. Temperature calculations are made from the basic data and these characteristics are separately shown.

A discussion of the advantages and disadvantages of each type of device is made relative to various uses, such as a hot gas source or high temperature source.

Appendixes are included for those who wish detailed operating information on each type of device.

PART I.

INTRODUCTION

A. Uses of Plasmas

Plasmas are found naturally throughout the universe, in the stars and nebula and also in our own ionosphere. Application of the properties of plasmas themselves began only recently, and their uses are becoming broader and wider each year. These applications range from pure research to rocket engines for space conquest. A discussion of the present uses and the direction of research in plasmas will place a good foundation under the objectives of this thesis.

1. Electric Arcs

The common electric arc has long been used for high intensity illumination from motion picture theatre projectors, to military searchlights and general night illumination. Attempts to improve the intensity and efficiency of these lamps have lead to many basic ideas behind arc production and maintenance.[5*] These have contributed much to an understanding of arc behavior. Much remains to be done; such as stabilization of high current-density arcs,[6] instabilities in the arc when influenced by magnetic effects, etc.[40] Not only are these problems to be solved, but the basic phenomena behind them is yet to be fully understood.[41]

At present the only extremely high temperature source (greater than 5,000°K) is the electric arc.[19] Most high temperature research

*Throughout this thesis, superscript numbers refer to the similarly numbered items in part VIII, LITERATURE CITED, used in support of statements preceding the superscript numbers.

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must be done in a high intensity arc. Present methods have produced temperatures up to $70{,}000^{o}$K.[26] Techniques are yet to be found that will retain this temperature source and make it a useful device. Measurements of temperatures above about $3{,}000^{o}$K are difficult and only rough approximations can be expected.[19, 1] The measurement of the properties of various materials in this temperature is very difficult. The behavior of the various materials in the electric arc at these extreme temperatures is almost unknown.[4] Theoretical behavior has been described, but the meager observations of actual behavior seldom correspond to such theoretical descriptions.

2. Plasmas

Our own ionosphere, as its name implies, is an ionized gas (plasma) which exists in the earth's magnetic field. Little is known about the reactions of the ionosphere to changes in the earth's magnetic field and to the sun's influence. These reactions have a great effect on the radio wave propagation on earth. The causes of the aurora displays (interactions in the ionosphere) are just beginning to be unfolded. More reliable communications from place to place on earth could be the result of an understanding of the ionosphere. Part of this understanding can come from basic research on all types of plasma devices.

3. Power Conversion

On the practical side, the application of the knowledge of plasmas to power generation may lead to a sizeable increase in overall plant efficiency and a supply of virtually inexhaustible fuel.

The application of magnetohydrodynamic (MHD) principles to a plasma flow for power generation (replacing the moving solid conductors in a generator with a moving plasma) shows promise of at least a 20 per cent overall improvement in present power plant efficiencies.[13] Work along this line has just begun, but vast results are forseen.[35] Present designs have produced only small amounts of useful power. High temperature materials to contain the hot plasma flow (2500-$5000^{\circ}K$) for long periods are almost unknown. Electric or magnetic methods of containing the plasma are now only theoretical concepts. Improving plasma properties (high conductivity with low temperature) with seed materials (materials to increase ionization percentage) is a problem at present. Almost no work has been done to optimize the various parameters involved in this type of power production.[31]

Production of the plasma to use in the MHD generator is a problem in itself. A large mass of material at high temperature and velocity is required for a high output. Present plasma research has been concerned with only small quantities of plasma. A big problem in present MHD generators is that they will only produce a DC output. Conversion of the energy to AC is costly. Direct AC production from the MHD generator has not been accomplished, and only theoretical ideas have been used in talk about such production. Little practical work has been done in this area. The problems in the DC MHD generator will keep engineers busy for some time before they can turn their sights to AC MHD generators.

Another approach to power production is the fusion process (combination of light elements to produce heavier ones). Holding

the plasma within a certain work area and not vaporizing the walls of the container is a serious problem. Producing the required high temperature is another serious difficulty. Interest in thermonuclear power is high since the fuel supply (mostly hydrogen) is virtually unlimited. This is extremely important in a world faced with a decrease in fossil and fission fuel supplies and an increase in demand for power.

4. Flight Applications

There are two ways in which plasmas can be applied to rocketry in outer space. One is the ion engine and the other is the plasma jet. Both of these are low thrust (0.01-0.5 lb.) devices that can provide high specific impulse rocket engines for high speed applications on long space journeys or more economical methods of achieving high orbits (20,000 miles) around the earth. Use is also found in a second or high stage rocket engine with various applications. Where the power requirements for the instrument package are high, this type of propulsion seems to be a most economical use of the facilities. The electric power supply of the payload may be used for the rocket engine during space position changes (or acceleration) and then shifted to the instrument package when the proper location is reached.

The ion engine is basically composed of an electron source (a cathode), some material to ionize with the electrons and a method to accelerate the resultant ions out of the engine for useful thrust.[10] The resultant beam must then be neutralized by ejecting electrons into it or a space charge will build up around the engine which will eventually neutralize any thrust generated. Many materials are used for

propellants; Cs, CO_2, He, Ne, A, H_2, N_2, Hg, NH_2, H_2O, K or almost anything that can be vaporized and placed into the engine chamber. Several types of accelerators are used; MHD principles, accelerating electrodes or wave accelerators.[37] Beam neutralization is a problem that has not yet been solved. On paper it looks easy, but practical problems are making this very difficult.[46] Another problem is the long dependable life required during which full power is necessary (about 100 days to the moon, 365 days to Mars).[3] A reduction in maximum thrust would lengthen the life required, and a failure would cancel the mission of the rocket.

Most plasma jets use an electric arc to heat the propellant to high temperature, then the plasma is expanded through a rocket nozzle to develop the required thrust.[11] Propellants used are mostly gases with low molecular weight for high specific impulse. Argon has been used in several experimental models. Research problems with the jet are varied: understanding of the energy losses, cooling techniques, methods of starting the arc at high altitudes and the most suitable propellant to use. Some consideration has been given to providing some type of acceleration to the jet for additional thrust. As with the ion engine, long life is a requisite. With the amount of thrust available (0.1-0.5 lbs.), the accelerating periods are long requiring an extremely long reliable lifetime at full power. Some applications have considered the use of radio frequencies to heat the propellant, but the energy transfer to the plasma decreases as the conductivity of the propellant approaches that of metals (skin effects).[38] This severely limits the temperature developed in the jet, but further study would determine if this would limit the optimum use of the jet.

5. Test Devices

Certain aeronautical problems use a plasma jet as a testing device to simulate high speed and high temperatures. The re-entry of missile nose cones places a severe test upon the nose cone. Supersonic velocity and high frictional temperatures would soon destroy the nose cone but for proper design. A test nose cone placed in the output of a plasma torch can be subjected to supersonic streams of high temperature (greater than 10,000°K), more extreme than those met in actual re-entry.

In supersonic wind tunnels, operating at high test altitudes, the temperature in the test portion of the tunnel decreases as the pressure drops. In order to simulate temperatures actually found at these altitudes, the air stream must be initially heated to a very high temperature in order to produce the required conditions in the tunnel.

6. High Temperature Applications

At present the only source of high temperatures is some type of plasma device (electric arc or plasma torch).[20] In fact at these high temperatures (over 5,000°K), almost all materials are in the form of plasmas (the materials have disassociated and ionized). These high temperatures have found application in various welding and cutting operations. They open up welding techniques for materials that have very high melting points and make possible high cutting rates on many difficult materials. Cutting rates for sheet steel are very high, and a clean cut is produced. Much work is being done in this area to produce a more efficient and usable device.[32]

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The high temperatures now obtainable make processes available which were not possible before, such as providing high melting point metals in ingot form. Another is the spraying of molten ceramic material on parts for protective coating in high temperature devices (jet engines, crucibles, ovens, gas turbines). These processes can also be carried out in an inert atmosphere, making this process available for highly reactive materials.

Chemical reactions which require high energy (such as combinations of N_2 and O_2) can be easily performed in the plasma. Experiments involving various ions are possible in the torch. The torch lends itself to a continuous process by its inherent flow characteristics.[45] The reaction zone is concentrated to a small area, and such "converters" could be small and simple in relation to other production methods in use.

7. <u>Astronomy</u>

Since the stars are composed of plasmas, more understanding of the action and reaction of small plasmas will lead to a further understanding of the stars and may lead to an understanding of their origin. The power sources within the star are of great practical interest on earth. An understanding of the reaction of plasmas to electric and magnetic fields governs the motion of all extraplanetary material. This understanding could lead to a basic foundation for the existance of the universe.

High energy particles (cosmic rays) are produced in the depths of space and attain great energies. The source of these particles seems to lie in the interaction of ions with magnetic and

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electric fields in space. These problems lead back to a beginning in the simple plasma acted upon by weak magnetic and electric fields. A logical extension of these effects may lead to an understanding of these high energy particles.

B. Statement of Problem

The purpose of this thesis is to make a comparison between two different methods of generating a plasma to operate a small plasma torch. One method uses an electric arc to generate a high temperature plasma; the other uses radio frequency power to produce the plasma. The plasma is contained in a suitable chamber, and a gas flowing through the chamber provides material for the formation of the plasma and also forces the plasma out through a nozzle producing a stream of hot gases which give the plasma torch its name. The comparison will be made on the basis of factors to be determined during the course of the thesis. Some factors to consider would be: temperatures produced in the jet, energy content of the plasma, flow rate of the gas, efficiency of heat transfer to the plasma, thrust of the plasma jet. These are the main characteristics of the plasma torch. Which property or combination will prove the best description of the torch will be determined later.

PART II.

HISTORICAL REVIEW

Research on plasmas was started in Faraday's time (the early 1800's) with investigations into the properties of electric arcs.[13] As electric power became available in large quantities (early 1900), arcing phenomena became important to the successful operation of many devices (e.g. motors and generators) especially when starting the device or stopping it. The first large scale use of arcs was for high intensity illumination (motion pictures and searchlights). These are still important uses of the arc. Most of the high intensity arcs of our time were developed on a hit or miss basis. Almost no theoretical work has ever been done into the fundamentals of arc operation.[9] Some German investigators have spent considerable amounts of time looking for the underlying phenomena of the electric arc.[7]

About the same time (1900), some thought was given to using magnetohydrodynamic effects to generate electric power directly from a hot plasma. Lack of adequate materials and the rapid development of the dynamo lead to a complete neglect of these MHD properties of plasmas.[14] With increased technology and the high demand for power, interest is again high for electricity generated from MHD effects. Recently (1959) devices have been demonstrated which produce power from MHD principles (AVCO, General Electric, Westinghouse). The efficiency of these fledgling devices was low, but the rewards for successful development will be high (e.g. a 20-25 per cent increase in overall efficiency of a large generating station).[14] Higher

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efficiencies seem possible when the process is understood enough so that optimizing principles can be applied.

The real impetus to the use of plasma and a beginning of a deeper understanding into the basic factors behind plasma behavior came with the need for a high temperature generating device to test the nose cones of missiles for re-entry from outer space.[36] This was about 1950. The study of the behavior of the nose cone in such a fiery blast (which could only be produced by an electric arc as a plasma jet) answered many questions that had no solutions prior to this. From this small beginning came a host of new uses for the plasma jet. Processes could be performed that had only been thought of previously (e.g. spraying ceramic coatings on parts for protection).

A newly expanding field (one that first started about 1959) is the use of the plasma jet as a rocket engine in outer space.[12] The advantages are great, and the expected specific impulse of this engine is much higher than that from chemical rockets. The thrust of such an engine (plasma) is small, but in outer space that is not as important a parameter as a high specific impulse (the time in seconds that a rocket engine will run on the weight of fuel equal to its thrust). No operating rocket engine using these principles is in use and none is expected for about a year,[22] but great expectations are held for this new use of plasma.

PART III.

THEORY

A. Methods of Plasma Generation and Limitations

1. DC Plasma Torch

The DC plasma torch is a very simple device (see Figure I). It consists of a chamber with an electrode at each end and a hole in one of the electrodes. Cooling is provided to eliminate excess heat which would destroy the device. Under pressure, gas is fed tangentially into the chamber to produce a swirling action around the electrodes. The positive column of the arc is in the space between the electrodes and in position to be blown out of the chamber by the gas.[39] This forces the plasma out of the nozzle thus giving the torch its name.

Which electrode is the anode is immaterial, the device will work either way. However, when the electrode with the nozzle is the cathode, the voltage across the electrodes is somewhat higher (about 10-20 volts). The transfer of energy to the plasma seems to be better with the higher gas flow, so the gas also acts as a coolant for the chamber. At high flow rates, the energy transfer to the plasma has been reported as high as 75 per cent with only 25 per cent being absorbed by the device.[33] With extremely high temperatures in the chamber (10,000-30,000°K), preventing the electrodes from vaporizing is a serious problem. However, with suitable cooling techniques, electrode erosion can be held to a minimum. The nozzle, with its long contact time with the plasma, is also extremely hard to keep cooled down to a point where it will not erode away. If the nozzle shows little effect of the hot plasma, it is an indica-

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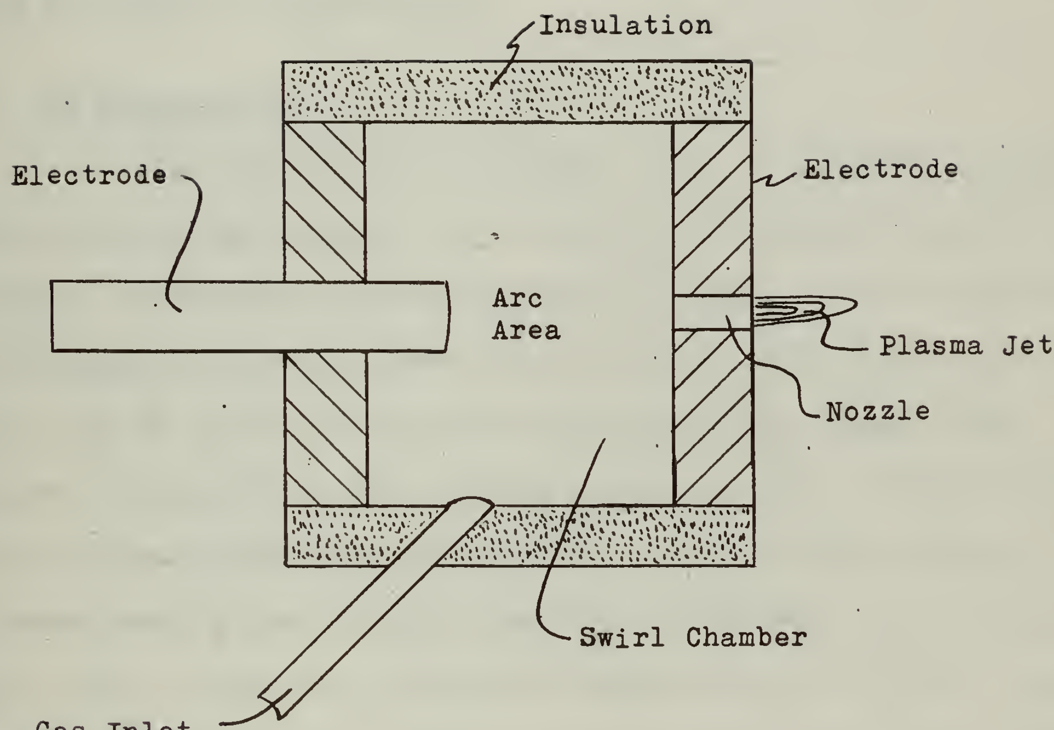

Figure I - DC Plasma Torch

tion of a low level of contamination. With seeding, the volume of plasma increases, producing a longer plasma jet.[34] Increased gas flow also increases the length of the jet somewhat. At these high temperatures, the radiation losses are also very high (about 150 kw/sq. in. of plasma surface at about 15,000°K, losses vary with the 4th power of temperature).

2. <u>AC Plasma Torch</u>

The single phase AC plasma torch is identical in construction with the DC plasma torch, the only difference being the power supply. Little has been done on the AC torch, but with almost all conveniently available power in the form of AC, its use would eliminate the DC converters needed to operate the DC plasma torch. Where direct DC conversion from thermal energy is used, the DC torch would have the most efficient applications. The AC plasma torch is an intermittant device, being turned on and off twice each supply voltage cycle. Also the electrodes change function each half cycle, and the variation in operation with the nozzle being both anode and cathode can cause some operating unbalance. Current limiting and control must be done with variable reactances to reduce unnecessary power losses.

The three phase AC plasma torch seems to have the simplest power source. The torch would be built somewhat as shown in Figure II. A split anode for the various phases also provides a means for arc rotation; the rotating vector of the three phase machine serves to rotate and stabilize the arc. A three phase device was built to provide a high illumination arc, but no other use has been found for it.[8] In the three phase AC torch, the ground electrode always

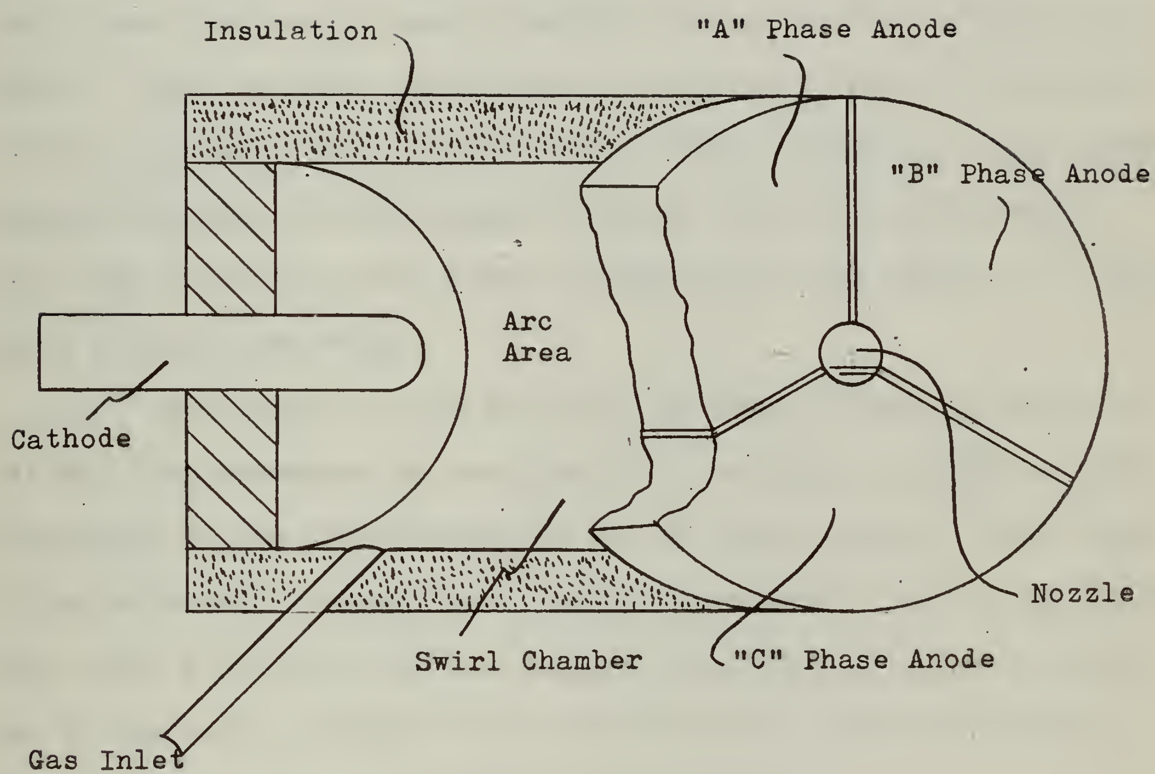

Figure II - Three Phase AC Plasma Torch

serves as the cathode and can be designed strictly for this function, unlike the single phase AC torch where each electrode changes its function. Insulation between parts of the split anode to prevent arcing outside the gun would be a problem at the temperatures involved. Design of cooling chambers would be more involved with the split anode and would require careful design to avoid extreme hot spots. Phase to phase short circuit protection would be necessary to limit current faults in the torch. Since almost all large power supplies operate with multiphase systems (and more efficiently), this type of device would seem to promise the best results in large scale plasma production.

The losses in the AC torch are very similar to those in the DC. The advantage of one type over the other is mainly a consideration of the characteristics of the power supply. Which type of device should be used for a certain application can be determined only after a study of all the factors involved in the application. The AC arc with its direct use of the available power would seem like the best choice for many earth-bound uses.

3. Radio Frequency Plasma Torch

The use of radio frequency heating techniques for generating plasmas[21] has one big advantage over the types of systems mentioned before. As seen in Figure III, there are no electrodes in the swirl chamber which must be in the plasma. The heat losses and contamination from these electrodes are eliminated. Plasma initiation is simple; the radio frequency generation method is self-starting, and the fields involved generate the plasma. A serious problem in any high temperature radio frequency generator is electro-

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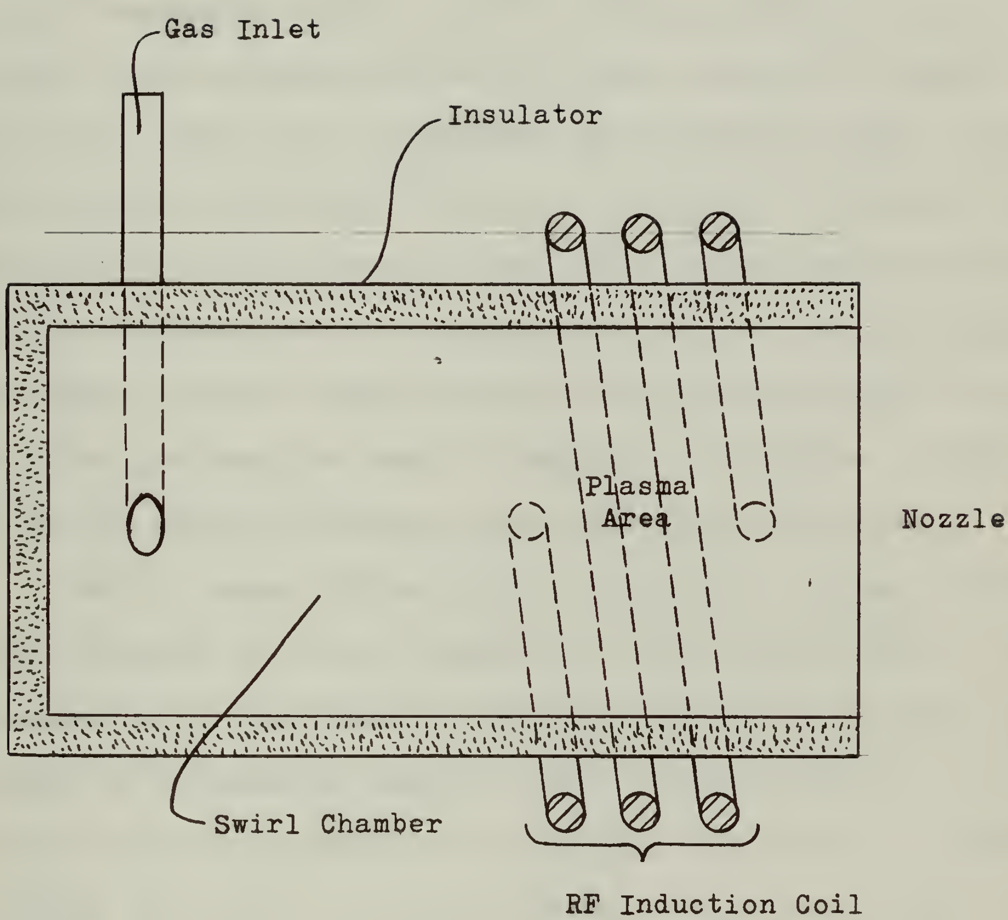

Figure III - Radio Frequency Induction Plasma Torch

magnetic field penetration depth into the plasma[16] (the depth at which the field is 36 per cent the value it was at the surface). As the plasma conductivity increases with temperature, the penetration depth decreases. Other variables being constant, the pentration depth varies inversely with the square root of the plasma conductivity. For argon at 10,000°K, the conductivity (at 1 atmosphere) is about 25 mhos/cm.[24] Using a 1 megacycle frequency source, the penetration depth is about 1 cm.[16] In a small generator, this would be no problem, but in attempts to generate a large diameter plasma volume, serious restrictions on the power generated in the plasma occur limiting the energy transfer to the plasma. Proper mixing of the plasma volume may solve part of this problem.

With a large surface area, the radiation losses would be high and certainly limit its operation at high temperatures. The power generated in the plasma is proportional to the frequency and the square of the maximum magnetic flux. Power considerations would certainly limit the diameter of the plasma, from about 2-4 penetration depths, if we are to get maximum use of the field within the plasma.[17] At a given temperature and conductivity, these considerations would limit the maximum frequency, but higher power in the plasma comes from increased flux or frequency. Each application would have an optimum size, frequency and flux available to make most efficient use of the radio frequency induction plasma torch. Design considerations are more difficult here than in the arc type generator. A complicated power supply is required to produce radio frequencies at a high power required for plasma torch applications. Considerably higher voltages (kv range) are involved with the insula-

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tion problem and hazard.

It is possible that capacitive coupling may be used as well as inductive coupling. However, almost no material on the use of capacitive coupling is available. Many of the advantages and limitations of induction coupling could seem to apply to capacitive coupling. An additional advantage would be the absence of the magnetic field since capacitive effects are entirely due to the electric field. Certain applications might prohibit inductive coupling, and the only possible alternative would be the capacitive coupled plasma generator.

4. Other Plasma Generators

Research into the properties of plasmas has been done in long tubes by passing a shock wave front down the tube and measuring the short time properties. The high pressure front in the shock wave boosts the temperature up to where the medium ionizes. Conditions can be carefully controlled and little contamination results.[25] Much useful information has been gathered as a result of these studies. The high temperature of high energy chemical reactions also produces plasmas.[27] Most familiar would be the exhaust of a rocket. However, the composition of this plasma is quite diverse and present design procedures can only handle simple compositions accurately. For other miscellaneous methods, see reference 26 in Literature Cited.

5. Common Problems of Plasma Generation

After discussing the various types of generating methods, it would be well to talk about some of the problems common to almost all of these plasma generating schemes. In all types of generators,

some means must be employed to start the buildup of ionized materials. The distance to the electrodes (in the generators that use them), under normal operating conditions, are much too far apart for breakdown of the gas by means of a high electric field. Several methods can be use:[23, 42] the electrodes are sometimes made movable so that the arc discharge can be started by touching the electrodes and then moving them out to the operating distance; a small wire is bridged across the electrodes to provide contact between them for arc initiation; a small radioactive source can be placed in the chamber to provide enough ions to get the normal arc going; also (as is done in this plasma torch) a radio frequency discharge is produced across the electrodes or auxilliary electrodes to start the main discharge. The radio frequency discharge is discontinued when the main discharge has begun. These last two methods also apply to generators without electrodes.

In many instances the per cent of ionization is not large enough at the desired power level of the device so some type of seed material must be used.[15] The seed material has a low ionization potential and so provides an initial supply of electrons to start the main avalanche of electrons and ions which increase the per cent of ionization. Seed materials are varied: cesium, potassium, rubidium, potassium carbonate and other salts of these metals. Sometimes other gases which easily disassociate are used to provide ions for the necessary seeding. Seeding can be easily accomplished by introducing the seed material directly into the arc chamber.

Various mediums have been used as the main constituent of the plasma: argon, helium, water and air being the most common. The

voltages used in the particular device (of the arc type especially) depend upon the first ionization potential of the gas. Gases with higher ionization potentials must use power supplies with high voltage capability. This also means that more power is required to ionize these gases and is a factor in determining the minimum power level in a device.

Many problems have been encountered in materials which can be used at the high temperatures involved in these plasma generators, and all classes of materials are involved, metals, non-metals, conductors and dielectrics. The problems involved in suitable power supplies are not a part of the investigation of this thesis. It will be assumed that the appropriate power can be provided at the terminals of the plasma generator.

All the arc discharge generators have one feature in common. The electric current from the power source is conducted through the ionized gas by electrodes. This current is directly responsible for heating the gas. Since the plasma contacts the electrodes, they become the major factor in its contamination. At high current densities in the arc, it is necessary to provide some control over magnetic instabilities in the discharge to maintain a stable arc. The usual method of rotating the arc involves both the use of mechanical means (swirling the gas in the arc) and magnetic fields to rotate the arc around on the electrodes. Although the normal discharge between electrodes is of considerable interest, this study is concerned only with the plasma. Therefore, in all the generators, the plasma is removed from the swirl chamber and forced out of the nozzle.

B. Measurement Problems

1. General Problems

Any measurements in the plasma are very difficult. The energy content of plasma is high and most measurements must be accomplished indirectly. No known material can be placed in the hot plasma and be expected to last more than a few seconds. Plasma energy calculations can be based upon the power input to the device and measurement of the various losses. The losses due to conduction and convection are easily measured. The change in temperature of the cooling water and its flow indicates the heat being carried away from the water-cooled parts of the device. The radiation losses which are the highest would be difficult to measure directly. Almost all the energy in the external jet must be lost by radiation as the jet is cooled below incandescence just a short distance beyond the nozzle.

The efficiency of energy transfer is important, since the optimum operation of the device depends strongly on this efficiency. Resistance losses in the electrodes are difficult to measure so they have been included as a part of the device. With large electrodes, this loss should be small compared with the power input. The measurement of the power input of the DC arc device is simple. In the AC and RF devices, some type of wattmeter should be used to show the power actually delivered to the device. The power input to the shock wave tube is calculated from the observed conditions in the wave. The energy in the chemical reactions must be calculated from knowledge of the reaction and the components of the reaction.

2. Temperature

The measurement of the temperature of the plasma is prob-

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ably the most difficult one to make. First it must be decided whether or not the plasma can be characterized by a temperature measurement. This means that the plasma reaches a state of equilibrium with its surroundings so that the losses balance the energy input. If a long enough time is allowed, then the plasma will reach an equilibrium state. These times have been reported in the order of 10^{-5} to 10^{-8} [28] seconds. Once a temperature measurement has been obtained, it must be determined whether it represents the temperature of the ions, electrons or neutral atoms. In general, the electrons have the highest temperature; ions and neutral atoms are much lower with the ion temperature being the higher of these last two. At high energy states, these three temperatures tend to approach each other.

At low temperatures a thermometer may be used, perhaps to 500°K. When the material begins to glow, some optical means can be used, such as a pyrometer. These optical techniques are good to about 3000°K.[2] This is about the limit of extreme accuracy in temperature measurements. The National Bureau of Standards is presently trying to extend the range of accurate temperature measurements above 2000°K. Above about 2000°K, the investigator is on his own and there are a host of methods which can be used.[29, 43] Which should be used must depend upon the equipment available and the results desired.

3. Temperature Measurement

Temperature measurement techniques divide themselves into several groups with a range of methods in each group. The first class of measurement techniques depend upon the density of the plasma and are closely related. The determination of one property

leads to the others. There are basically four types of density measuring techniques. Two similar methods use electromagnetic waves (x-rays or microwaves) or alpha particles to measure the density of the medium. A third, the propagation of sound through the plasma, is also a measure of its density since the velocity changes with changes in density. The last uses a gas or medium that is radioactive (this has been used with mercury), the amount of radioactivity given off from various parts of the plasma is directly related to the density of the plasma. Each of these techniques has limitations which would apply to the system under consideration (e.g. using radioactive materials in an open system might create hazards that the investigator would rather not cope with).[44]

Another measurement technique uses spectral measurements. Several specific methods can be used. The presence of certain spectral lines is a general indication of temperature minimums (the temperature must be at a certain level before the energy indicated by the line can exist). The absolute intensity of a particular line is also directly related to the temperature. These absolute intensities are difficult to measure, so many times relative measurements are made. These measurements can be made relative to a known intensity standard or relative to the intensity of two different spectral lines in the plasma spectrum. Another important spectral method uses the line broadening due to Doppler shift to measure the temperature. This technique does not depend upon line intensities, except that the line be bright enough to use for measurements.[30]

When the temperature is high, a good approximation can be made of the surface temperature of the plasma. This method assumes that the convection and conduction losses are small compared to the

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radiation losses. Above about 1000°K this is usually true. Standard handbooks relate the losses to the surface temperature of the body. Typical of these would be

$$\text{Radiation Losses} = 37e\left[\left(\frac{T_2}{1000}\right)^4 - \left(\frac{T_1}{1000}\right)^4\right] \text{watts/in}^2 \quad 18$$

Where T_1 (in degrees K) is the ambient temperature, T_2 is the body temperature and e is the body emissivity. For the high temperature case, this would reduce to

$$\text{Radiation Losses} = 37\left(\frac{T_2}{1000}\right)^4 \text{watts/in}^2$$

Assuming only radiation losses from a body, a knowledge of the size of the losses and the surface area of the body in question would lead to an approximate value of the temperature very simply. This method can be used only when the losses are well known, and the shape of the body can be easily determined.

Other methods can be used as well. The measurement of refractive index, either from x-rays, microwaves or sound waves. The absorption properties of the plasma to light would also be a measure of the temperature of the plasma. These methods would require special techniques to adapt them to any particular device.

4. Other Measurements

Certain other measurements of the performance of the torch must be made. These measurements include a wide range of parameters. The pressure surrounding the plasma is important in certain applications (plasma rocket engines). The thrust of the jet evidences itself in a back pressure on the gas supply system. The thrust to be measured is small (0.01-0.5 lb.), so the back pressure is also small.

Measurement of these small changes in pressure is necessary to determine the useful output of a plasma rocket engine. The thrust can be correlated to the temperature, so that this measurement could be used to determine the temperature changes in the arc chamber.

Certain electrical measurements must be made ranging from direct current to radio frequencies. The wide range of frequencies requires a variety of instruments. Voltages from about 30 volts DC to several thousand volts at radio frequencies are in the measurement range. The current in almost every case is large (up to 1000-1500 amps DC and possibly 200 amps at radio frequencies for a large radio frequency generator). The extremes of each range (voltage and current) present problems which must be overcome before accurate measurements can be made. Either a wattmeter or some type of phase measurement must also be made to determine the power flowing into the generator.

When determining the energy in the plasma, the flow rate of material through the arc is important, in fact, almost all of the plasma generators employ some flow measurement problems if only to measure the amount of cooling water used. With a gas flow, a critical orifice flow meter is suitable as it can be used for a variety of gases by simply changing the calibration chart. Inlet pressure on this type of flow meter usually has a minimum (about 20 psi), and a 50 per cent drop in pressure across the orifice is necessary for linear operation.

In certain situations, the contamination of the plasma by the surrounding chamber and electrodes is important. Chemical analysis of the products from the plasma or a spectral analysis of

the jet would be suitable means for making these measurements. The per cent of ionization of the plasma is important in theoretical considerations of the plasma behavior. Methods of determining the per cent ionization are based on a measurement of the electron density. The amount of seed material in the plasma makes a marked effect on the per cent ionization. The amount of seed material could be determined either by the increase in ionization or by an analysis of the plasma output to find the per cent of seed material present.

PART IV.

EXPERIMENTAL PROCEDURES

A. Operation of a DC Plasma Torch

1. Materials and Apparatus

The materials and apparatus for operation of the plasma torch were assembled in the Metallurgical Engineering Laboratory. A 25 kw welding generator rated at 600 amps and 40 volts DC was the main source of power. Its location determined the actual layout of equipment. This welder had an extremely drooping voltage characteristic and was able to maintain satisfactory current control. The open circuit voltage could be made as large as 110 volts DC. The gas to operate the torch was obtained from standard 220 cubic foot cylinders. The pressure was reduced before being used in the torch. Argon was the gas used, but compressed air was also available at the bench. Cooling water and a drain were convenient to the torch location. A high frequency welder control was used to initiate the arc in the chamber.

The torch itself had been constructed earlier and had seen some severe service prior to its present use. When the torch was first opened for inspection, the cathode surface and inside of the nozzle were severely eroded and pieces of tungsten had been blown onto the carbon anode. This area extended about one inch into the nozzle. The inside of the chamber was charred. Before attempting to operate, the entire torch was put back into nearly original condition.

a. Torch construction. A cross section of the DC plasma torch is shown in Figure IV. The torch is about 12 inches long and

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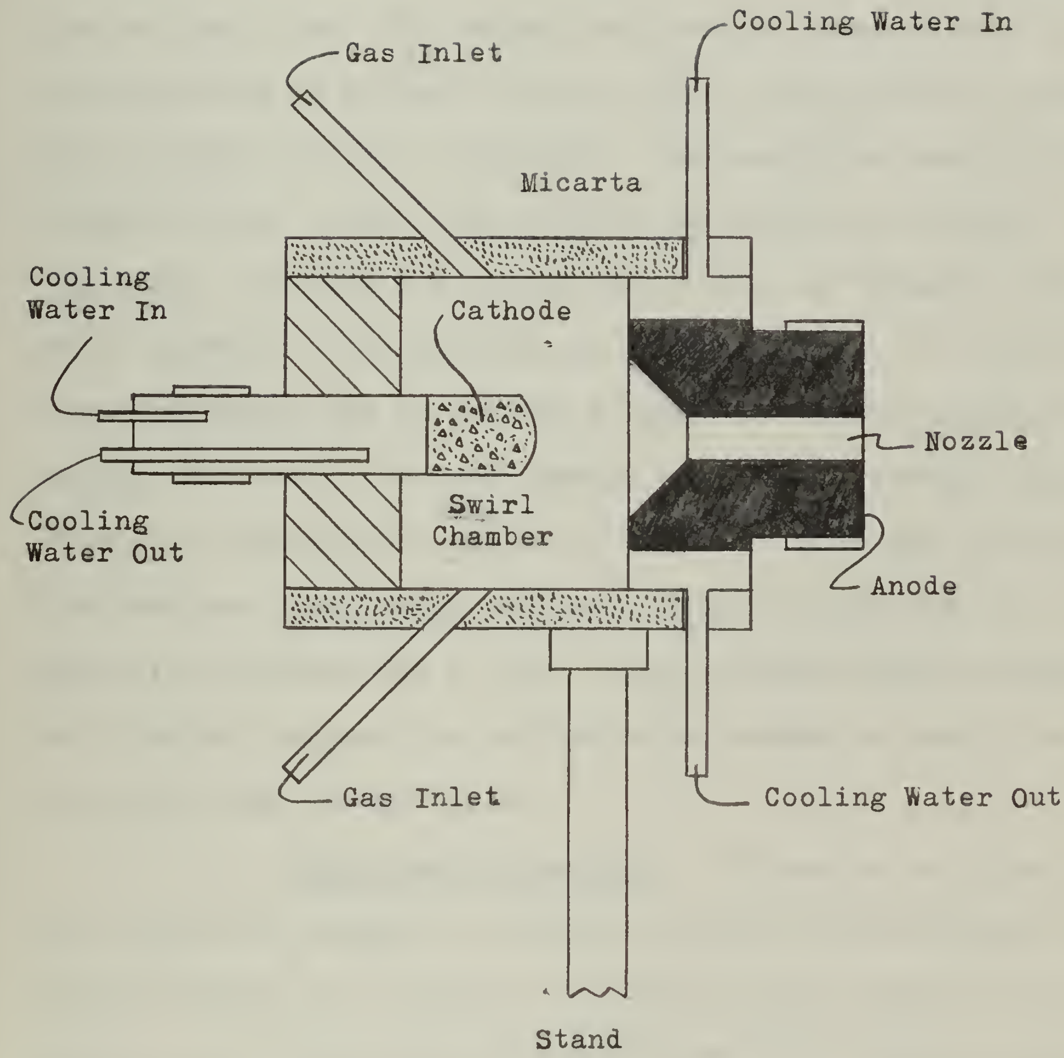


Figure IV - Actual DC Plasma Torch

4 inches in diameter. The nozzle diameter is $\frac{1}{2}$ inch. The torch was designed to operate about 15-30 seconds with an input power of 15-25 kw. For these power levels, the electrodes were provided with cooling water chambers and were massive enough to carry heavy currents during operation. The cathode was made of brass with a tungsten wearing piece in contact with the arc. This piece was rounded off with a radius of about $1\frac{1}{2}$ inches. The anode was constructed of a large block of carbon. The nozzle, which was an integral part of the anode, was simply a $\frac{1}{2}$ inch hole with a 45° chamfer inside the swirl chamber. This chamfer has a dual purpose, to provide the nozzle entrance and to provide a large arc contact surface on the anode. The main structural member held the electrodes apart and formed the confines of the swirl chamber. With dielectric properties and heat resistance required, "Micarta" was used for this piece. The wall thickness was $\frac{1}{2}$ inch. This provided enough thickness for drilling and tapping the various holes needed to mount the torch and to mount items on the torch.

b. Measurement apparatus. To measure the flow of gas into the swirl chamber, a critical orifice flow meter was used. The meter measures the pressure maintained on the high side of a standard orifice, and this reading was correlated to a reading of gas flow. See Figure V for such a chart. Standard orifices were available to measure flow rates from 8 to 2400 cubic feet per hour. Correction factors are available for almost any common gas that could possibly be used.

The voltage measurements were made with a standard 150 volt DC voltmeter. The current measurements were made with a 50 mv DC

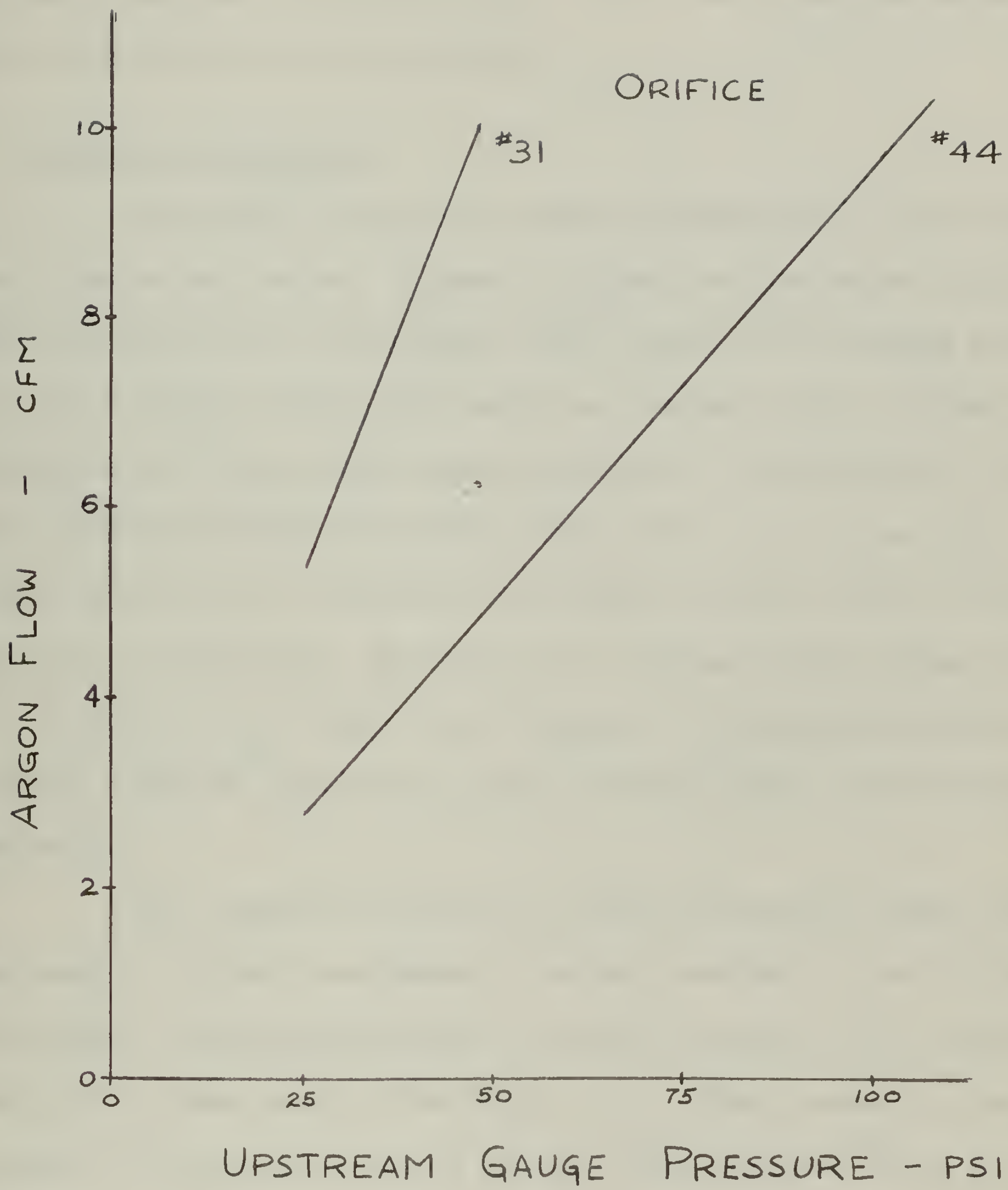


Figure V - Characteristics of Critical Orifice Flow Meter

voltmeter and an 800 amp shunt. The length of the plasma jet was compared against a standard ruler. The flow of cooling water and its temperature were not measured.

2. Method of Procedure

In order to show the interconnection of all the apparatus, two figures are needed. Figure VI shows the electrical circuit and the location of all the meters, while Figure VII includes a diagram for the cooling water system and also the gas supply system. Certain items in the figures need some explanation. In Figure VI, the control switch controls the power to the torch and the gas flow. The gas flow cutoff was necessary to prevent gas flow when the torch was not in operation. Because of the high gas flow rates, one tank of gas would soon be used up if the gas were unintentionally left flowing. The HF control unit was used only until the torch was going well.

The clamp in the water cooling system (see Figure VII) was used to balance the amount of water provided to the cathode and anode. The anode requires the most cooling so the clamp was adjusted to send most of the water to it. This seemed to produce adequate cooling as the torch did not once overheat while in operation.

Once the torch was set up properly, its operation was simple. The cooling water was turned on, the gas supply pressure set and the control switch closed. When the HF starter was turned on the torch should start. The voltage and current could be varied at the welder for the desired power setting. When it was desired to turn the torch

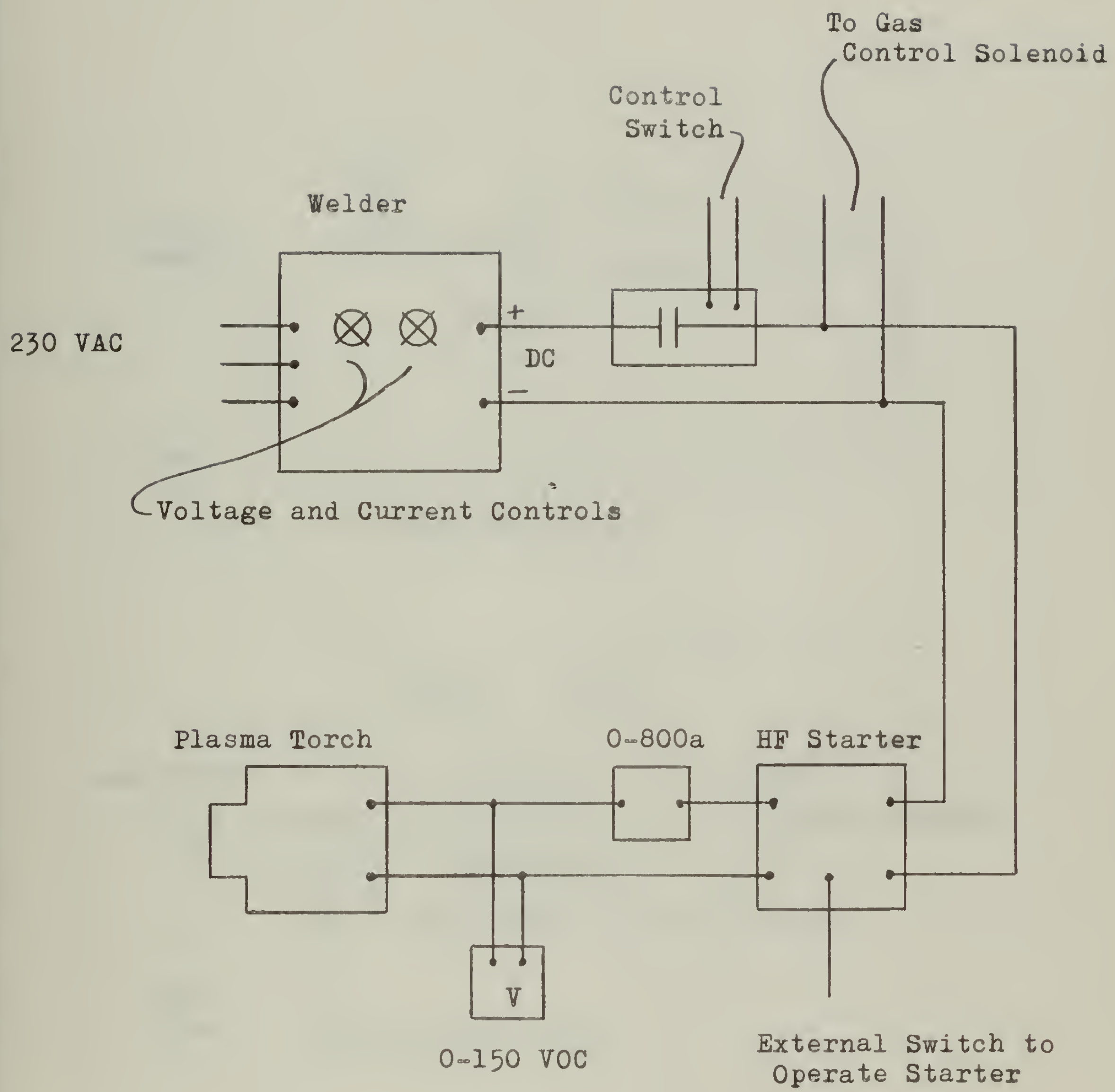
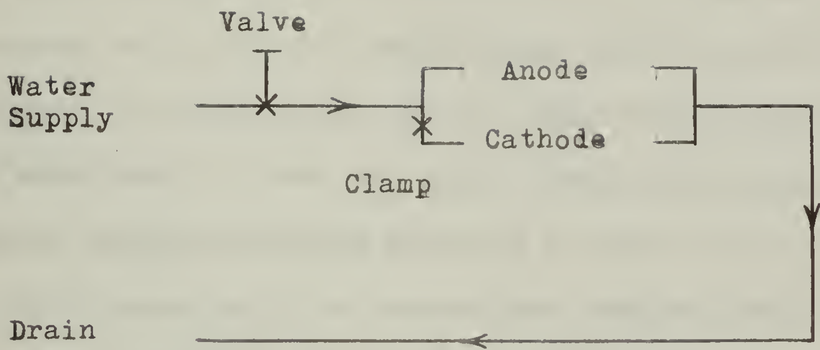
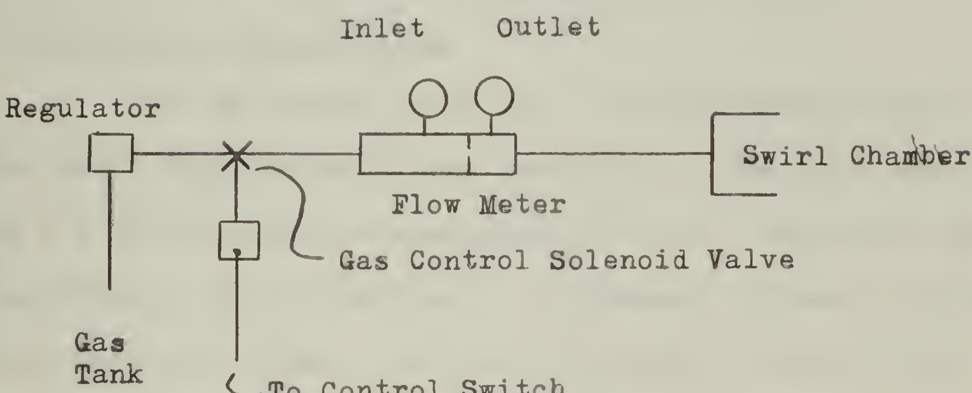


Figure VI - Electrical Circuit of DC Plasma Torch



a) Cooling Water



b) Gas Supply

Figure VII - Mechanical Connections

off, the control switch was turned off. For more detailed operating instructions, see Appendix I.

With the torch operating, the data taking process began. This was hindered by the 30 second time limitation on continuous operation of the torch. During each run, the gas flow was held constant and the power input and jet length were measured. About 35 runs were made to cover the entire range from a gas flow low enough to cause uneven arcing to one high enough to blow the arc out. At the end of each run, the current was reduced until the torch went out. This indicated the minimum power required to sustain the torch in operation.

B. Operation of an RF Plasma Torch

1. Materials and Apparatus

The RF plasma torch was assembled and operated in the Electrical Engineering Plasma Laboratory. The main source of power was a 1 kw RF generator operating at 10 mc. Argon was the only gas available for this experiment. A standard cylinder provided an adequate supply of argon. To start the torch a small "tesla" coil was used. The apparatus was small and with the RF generator mounted on wheels a very portable unit was finally assembled. It could be operated anywhere adequate power was available.

a. Torch construction. The torch as constructed in the E.E. machine shop is shown in Figure VIII. In size, the torch is about 8 inches long and about 2 inches in diameter. The swirl chamber and nozzle have a diameter of 3/4 inches. The prototype torch was able to operate at power ranges up to 2 kw for long periods of time. The body and sleeve of the torch were made of brass. The auxiliary elec-

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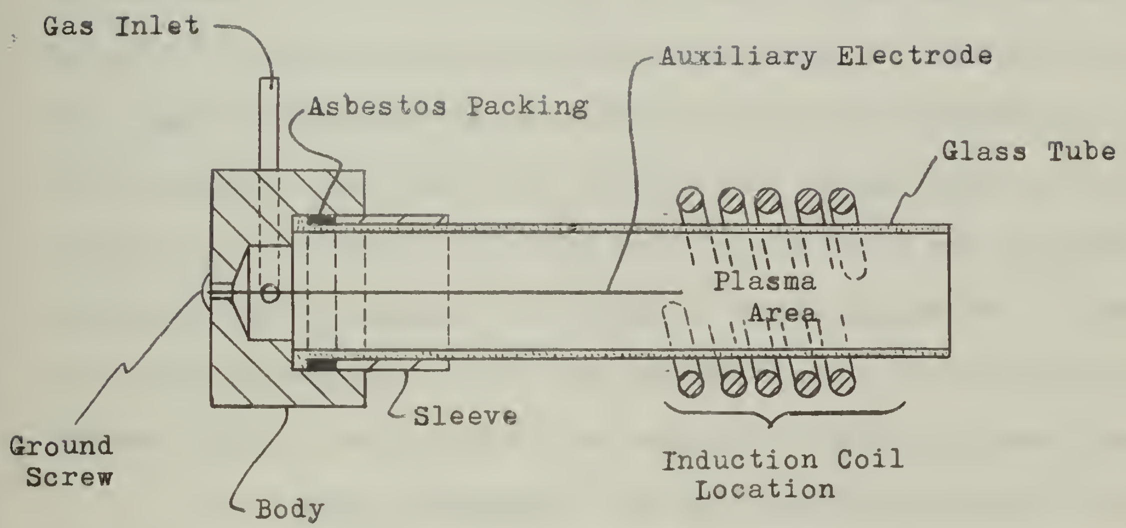

Figure VIII - Actual RF Induction Plasma Tube

trode was made of carbon or graphite. The glass tube was made of "Vicor", a special high temperature glass. This glass tube was held in place in the body by an asbestos packing. The packing compensated for differential expansion between the brass and "Vicor". The gas was fed into the body of the torch tangentially and swirled about in the gass tube until it exited the tube. This swirling motion helped to stabilize the arc and confine it to the center of the tube. The high velocity gas just inside the glass walls provided cooling for the glass. The torch was mounted in a clamp which in turn was clamped to a vertical rod. The body of the torch was grounded. The induction coil consisted of 5 turns of wire, $1\frac{1}{4}$ inches in diameter and 1-1/8 inches long. The coil was mounted in the area shown in Figure VIII and connected to the terminals of the RF power generator.

b. Other equipment. The gas flow measurements were identical to the previous experimental set up and Figure VII b) shows the actual equipment used. The control switch shown was made to operate the gas control solenoid only. A small RF starter was used to initiate the torch plasma. The length of the plasma was compared against a standard ruler. No external cooling was used.

2. Method of Procedure

The connections for the gas supply system are shown in Figure VII b. The electrical connections were very simple. The induction coil was simply connected to the terminals of the RF power generator. The glass tube of the torch was then positioned so that it slid into the induction coil without touching the coil. The auxiliary electrode just protruded into the end of the coil.

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After the torch and associated equipment were set up and properly adjusted, the operation of the torch was as follows. The RF power supply was warmed up. The gas flow was started with the control switch. The RF power was turned on. At high power settings the torch should start immediately. At low power settings it was necessary to place the small RF starter near the end of the glass tube. The torch should now start. In order to turn the torch off, the RF power supply was turned off, and the gas was shut off. For more detailed operating instructions, see Appendix II.

After the torch was operating, the gas flow was varied until the torch was operating at its best. At this point the data was taken to determine the power delivered into the plasma, and the plasma volume size. Since this torch could operate for long periods of time, only a few runs were needed to obtain the necessary data.

PART V.

RESULTS

A. DC Plasma Torch

With the wide range of parameters involved, it was felt that the torch should remain in the same condition throughout the experiment. While taking data, the torch was operated at the lowest practical power level. The interior of the torch was examined at regular intervals during the experiment for signs of overload. As a result, the torch was not overheated and the interior of the torch was in almost original condition at the end of the experiment. It was not necessary to return the torch to the shop for repairs at any time.

In the beginning of this study, there were no indications of which parameters would be the best to use when optimizing the torch operating conditions. As a result, much more data was taken than necessary in order to have an over-all picture of the torch operation. The gas flow was varied over a wide range; from low values where the swirling gas had little effect on arc rotation and the torch sputtered and operated roughly, to high values of flow where the gas velocity was high enough to blow the arc out.

In order to provide a uniform set of data, the following procedure was used several times for each value of gas flow. The torch was started and allowed to operate smoothly for a few moments. Then the power was reduced to the lowest level at which the torch would operate. Data was taken at the beginning and end of this procedure. The temperature was calculated from the losses and the

size of the plasma jet (see Part III, Theory, B, 3). Knowing the gas flow, the nozzle velocity was computed from the above temperature and Charles's Gas Law.

The first operating point chosen for the torch was the distance of the electrode gap. Table 1 shows typical data relating the electrode distance to the other variables of the problem. The power input was held approximately constant, and the temperature calculated for each point. As a result of this data, the electrode gap for the rest of the experiment was set at 0.25 inches. Argon was the only gas used. Air would not operate in the torch at the power levels used.

With the electrode gap held at 0.25 inches, the power input was held relatively constant, and the other parameters of the torch were measured. Table 2 shows these results. The variations in these parameters were uninteresting from an optimizing point of view. There were no maximums or minimums, so no optimum operating point was apparent. Thus the characteristics of the torch with constant input power were not used to find an optimum point.

Next the torch was operated with the minimum power possible. In Table 3, data obtained with the torch operating in this fashion is shown. The data is interesting in that minimums of power and maximums of temperature seem to occur. In order to more clearly see this relationship, Figure IX graphically illustrates the data of Table 3. This is clearly the data to use when determining the optimum operating point of this torch.

During all operating periods, no change in chamber pressure was noted indicating no sizable thrust from the torch. The torch was not set up to directly measure thrust.

TABLE 1

DC Plasma Torch -

Gas Flow vs Electrode Distance

Gas flow cfm	Electrode Distance in.	Power input kw	Jet Length in	Temperature ^{o}k
4.0	0.25	10.03	0.75	4200
4.8	0.25	9.09	1.00	3700
4.0	0.44	9.64	0.87	3900
4.8	0.44	8.64	0.87	3800
4.0	1.00	9.28	1.00	3700
4.8	1.00	9.75	1.00	3800

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TABLE 2

DC Plasma Torch -

Gas Flow vs Gas Nozzle Velocity

Gas flow cfm	Power input kw	Jet Length in.	Gas Velocity ft/sec
0.7	8.41	1.00	110
2.0	5.99	0.63	300
3.1	8.99	1.00	450
4.0	10.03	0.75	670
4.0	---	---	50
4.8	8.98	1.00	700
6.0	9.00	1.00	930
6.8	8.60	1.12	970

Electrode Gap held at 0.25 inches

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TABLE 3

DC Plasma Torch -

Gas Flow vs Minimum Power

Gas flow cfm	Power input kw	Jet Length in.	Temperature °k
0.7	8.41	1.00	3600
1.2	4.04	0.50	3600
2.0	5.99	0.63	3700
3.1	4.82	0.63	3500
4.0	3.60	0.38	3700
4.8	3.04	0.25	4000
6.0	4.81	0.50	3800
6.8	8.60	1.12	3600

Electrode Gap held at 0.25 inches

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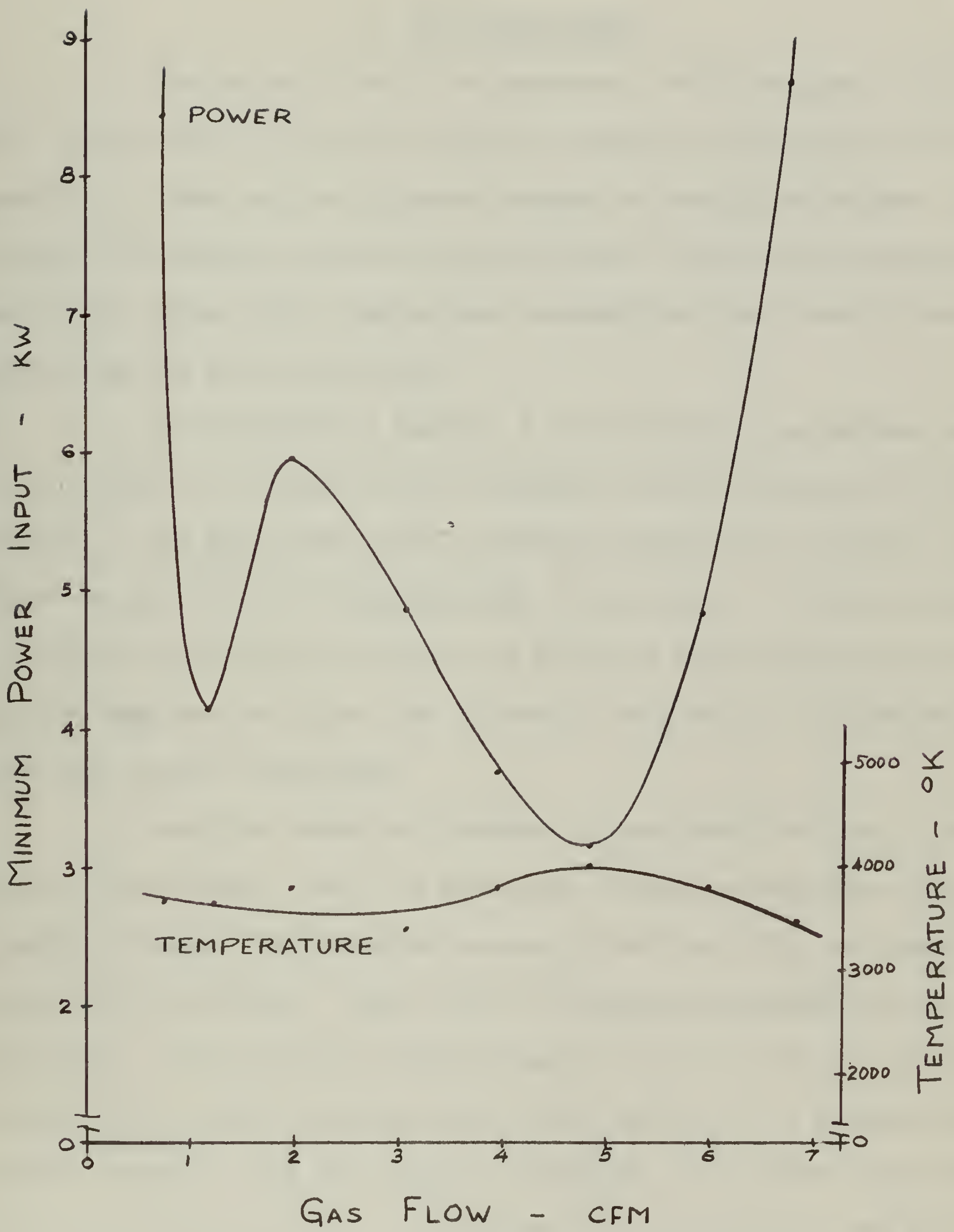

Figure IX - Minimum Power Characteristics for DC Plasma Torch

B. RF Plasma Torch

The RF torch was also operated at minimum power levels. The torch operated well and could be operated continuously for long periods of time with no apparent damage to the glass chamber. The longest continuous run was eight minutes. This long operating time made data taking much simpler and quicker than was possible when operating the DC plasma torch.

As discussed in Section A of this Part, parameters had to be chosen that would reflect optimum operating points for the torches. The only such clearly defined parameters appeared to be those of gas flow and minimum power to operate. In order to make a comparison on these factors, the RF torch was operated only to obtain this desired data. As a result, this half of the experimental work was quickly completed.

Once the torch was started, it was operated over a range of gas flows from a low flow where the plasma was unsteady, to a somewhat higher flow than was necessary for the torch to operate smoothly and quietly. This data is represented graphically in Figure X. The operating characteristics of the torch were relatively flat. The temperature and power input to the plasma remained almost constant over the range of interest. As before, the temperature was calculated from a knowledge of the losses and the size and shape of the plasma.

As the torch had no electrodes, no other data was necessary to find an optimum point of operation. The only other possible variable was a change in configuration of the induction coil. Two sizes and spacings of coils were tried with similar results. With

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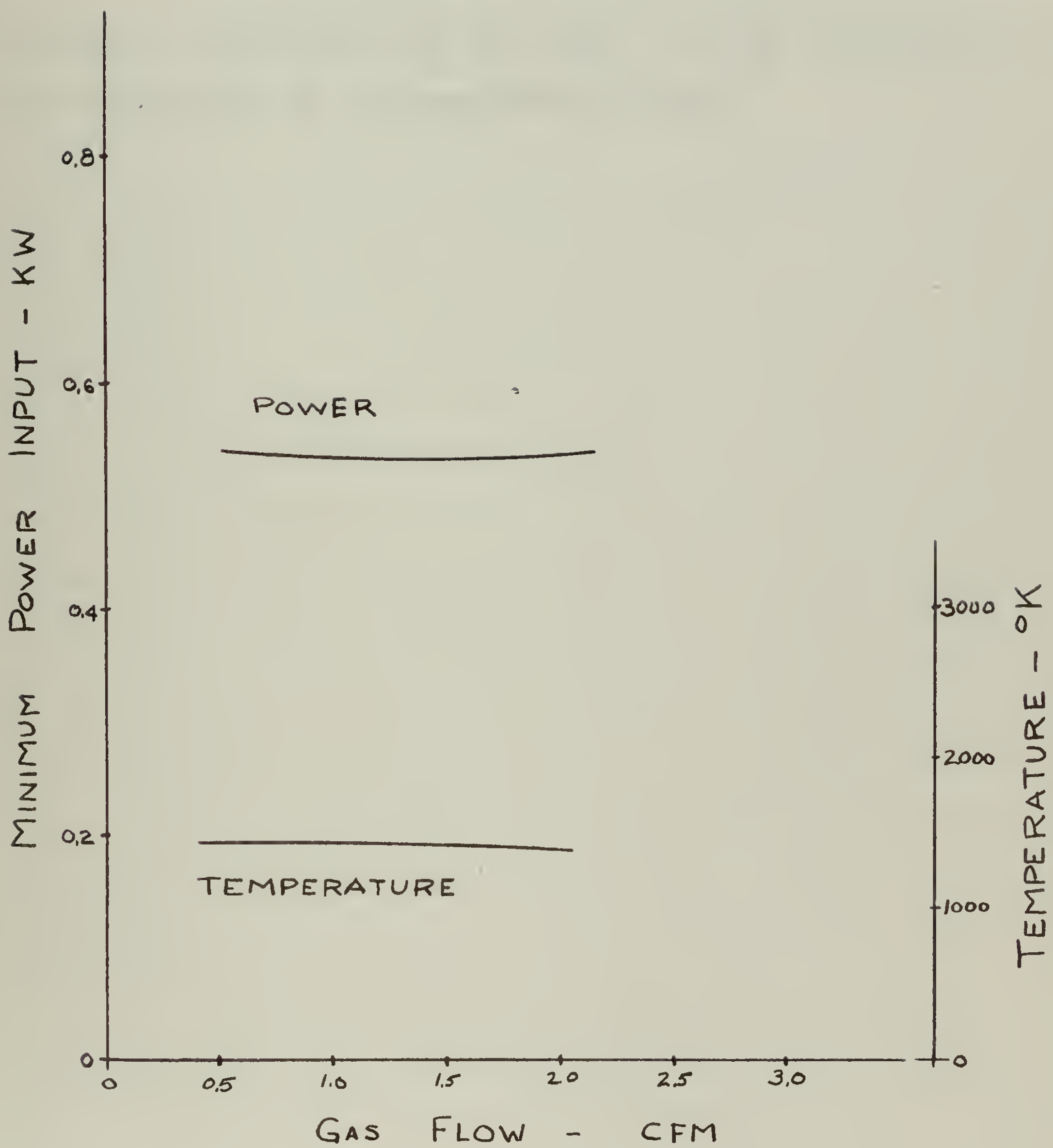

Figure X - Minimum Power Characteristics for RF Plasma Torch

no other parameters to optimize, the data on the RF torch was complete for a comparison with the DC torch.

No pressure changes were noted when the torch was in operation indicating very low thrust. It was not possible to get any indications of the magnitude of thrust.

PART VI.

DISCUSSION

A. Comparison of DC and RF Plasma Torches

Before a comparison is made between the operation of the torches, the characteristics of each should be presented in a simple form. It was decided that this could best be done by choosing the optimum operating conditions for each torch. A look at Figure IX will show an obvious operating point for the DC torch, that is where the temperature is a maximum for a minimum power input. Figure X shows the same operating conditions for the RF torch. The temperature has no definite maximum, so the smoothest operating point was chosen. To present these figures in convenient form, Table 4 was prepared to show each torch at its best. Most of this data has been presented before. The values now shown for the first time have been calculated using this previous data. All the major parameters of each torch have been listed for easier comparison. The following discussion will make a torch comparison on the basis of each of these parameters.

The range of gas flow of each torch overlapped, but the optimum flow for the torches was several magnitudes apart. This optimum flow appears to occur where the arc swirling action of the gas is creating a stable, well-behaved plasma, but where the cooling action of the gas has not yet begun to cool the plasma excessively. Below this value the plasma is noisy and the torch operation is uneven; above this value the gas cools the arc down until it finally blows out.

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TABLE 4

Tabulation of Optimum Operating

Conditions for Each Torch

Parameter	RF Plasma Torch	DC Plasma Torch
Gas Flow	1.0 cfm	4.8 cfm
Power Input	0.53 kw	3.04 kw
Temperature	1400°k	4000°k
Jet Length	1.00 in.	0.25 in.
Nozzle Velocity	26 ft/sec	700 ft/sec
Thrust	could not measure	

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[illegible]	[illegible]	[illegible]
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The power input shown is the minimum power required to sustain the torch in operation. The power requirements of the DC torch are about 6 times those of the RF torch. Although the physical size of the torches is not very different, the power requirements vary widely. The original full power design requirements are about 10 times greater for the DC torch than the RF torch.

Temperature is a difficult parameter to measure, so in this case it has been calculated. The same technique was used for each torch. The value of the temperature calculated represents only the temperature at the visible surface of the plasma. The interior temperature should be from about 1.2-2.0 times greater than the surface temperature. The absolute value of this calculation may not be very accurate, but the relative magnitudes should be sufficient for a valid comparison. The RF plasma temperature was about 1/3 that of the DC torch temperature.

An indication of the useful plasma volume is given by the jet size. On the DC torch, this is the length of the jet beyond the anode. The RF torch data is for the length of the plasma volume. The useful plasma volume of the RF torch is several times larger than the corresponding volume for the DC torch.

The variation in nozzle velocity is the most marked. This large variation is mainly due to the great difference in the diameters of the nozzles, but the temperature differences are also an influence. The velocity calculated is only the average velocity, and for laminar flow the maximum velocity should be somewhat higher (about 1.5-2.0 times).

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It was not possible to measure the thrust, so no comparison was made of this parameter.

After a comparison of all torch parameters, it is apparent that the RF torch is the smaller by far of the two torches. Therefore, the capacity of the DC torch is several times greater than the RF torch. The RF torch has one major advantage in that it has a larger plasma volume. Even after such a comparison of parameters, it would not be possible to say that one torch is better than the other. The uses of the torch would have a great bearing upon the ultimate decision.

B. Uses and Applications of Each

The DC plasma torch operates at higher power, flow rates and temperatures than the RF torch. As a result, it is the better device to use for applications requiring high energy content. It would be ideal as a high temperature generator, if contamination was not an important factor. It would also work better as a source of plasma for MHD power generation, providing high flow rates at high velocities. It would also be very good as a test device, for example, for re-entry problems.

The RF plasma torch is better suited to small energy applications. It would be well suited to test small parts at high temperatures, or provide a small plasma volume for experimental purposes. In those cases where contamination must be kept very low, the RF torch is the outstanding choice. There are no materials in the torch to vaporize and contaminate the plasma. Argon, as the gas, will not combine with any materials and provides a clean heat source.

No comparison can be made for the use of either torch for flight applications. Without thrust measurements, no supporting statements can be made. However, availability of only one type of power supply may eliminate one or the other torch from consideration as a booster rocket.

C. Limitations of Findings

It must be recognized that the measurements made during the course of this experiment are not of a precise nature. The characteristics of the torches were such that accuracies of 10-20 per cent were sufficient to make valid conclusions. The experiments were designed to determine the optimum areas of operation for each device and not to pinpoint exact operating data for a rigorous examination of the torches operation.

During the course of the calculations, certain assumptions had to be made in order to complete the computations. The computations involved in data on nozzle velocity and jet size were easily obtained. The temperature computations involved the only radical assumptions. The technique itself neglected losses other than radiation in order to compute the temperature. At the high temperatures involved, this assumption is a reasonable one to make. One other assumption made concerned the energy transfer to the plasma. It was assumed that it was constant over the entire range of gas flows. This was the best approximation that could be made in view of the measurements made during the experiment. It should be expected that the efficiency of heat transfer should increase as the gas flow increases until at high flow rates the efficiency drops due to the gas cooling effects.

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It must be remembered that the torches were optimized at the lowest power level for each torch. When extending this data to high power ranges, care must be used, since the extrapolation of data will probably not hold closely. The data presented will make a good base upon which to begin studies of the torches at high powers.

The results indicated an optimum operating point, but it must be remembered that this was chosen only as a basis for comparison. Each torch can be operated under conditions widely different from those optimum ones. As the power input increases, the range over which the torches will operate becomes larger. No search was made for an upper power limit, since the torch might be destroyed if the power level became too high.

D. Future Areas of Investigation

1. Optimizing Size of Device

During the course of operating the DC plasma torch certain design changes were considered to improve the torch efficiency. A design change with larger cooling capabilities and a smoother flow of plasma through the anode was considered. A venturi nozzle was considered to keep the plasma flow as smooth as possible in order to reduce the losses to the nozzle walls. The entire anode with nozzle would be shortened to about 1 inch, cutting the time the plasma would be in the nozzle and reducing the losses to the anode. The carbon block would be only large enough to provide a high temperature resistant surface (about 1 inch in diameter). The cooling jacket would be made larger (about 1 square inch in cross section). Some means would be provided to inject the water near the outer edge of the jacket and drain it out near the center of the torch. It was felt that with

these changes the anode heating would not become extreme and the torch could operate for longer periods of time at higher temperatures. Due to time limitations these changes were not made.

As the RF torch became an operational item, thought was given to increasing the coupling between the RF generator and the plasma. Two single-layer coils were used in the experiment, but other combinations might give better results; varying the diameter of the coil to make a more uniform field, using closer or wider spacing of turns. A pancake coil design was suggested but was not tried. Such a design would concentrate the field in a short part of the chamber and could produce higher temperatures. A single frequency was used, but the size of the torch suggests that various frequencies be tried until the optimum one is found. The diameter of the tube should be about four penetration depths at the plasma conductivity produced. As the conductivity changes with increased power, a changing frequency might maintain maximum energy transfer.

2. Optimizing Output

Once an application has been chosen for either of the devices, the output of the torch can be determined (e.g. temperature, hot gas flow, plasma, etc.). At this point the best operation for that parameter should be determined. This would mean operating over the entire range of the torch and maximizing the output while trying to minimize the other parameters. This was done in this thesis for the most obvious parameters, but it was beyond the scope of this study to do so for all the parameters.

3. Efficiency

As was mentioned before, the energy transfer to the plasma was assumed constant, but the author feels that it is not. In order to measure the efficiency of heat transfer, more elaborate measurements have to be made. An energy balance between the input and all the losses would have to be made. In this experiment the power input was measured but the losses were not. Some scheme to measure these losses would have to be added to the apparatus in order to compute the efficiency of heat transfer. If the energy in the plasma itself could be directly measured, then a direct measurement of efficiency would be possible. This approach is even more difficult than the first.

PART VII.

CONCLUSIONS

A. The two torches complement each other providing a wide range of operating parameters. The RF plasma torch is suitable for power levels above 0.5 kw to the lower range of the DC torch. The DC plasma torch fills in the power range to about 25 kw. The other parameters have much the same relationship in their range of interest.

B. It was determined that the DC plasma torch operated the best when the gas flow through the torch was about 4.8 cfm. This optimum flow rate was determined only for argon and an electrode gap of 0.25 inches.

C. It was concluded that the RF plasma torch would operate the best when the gas (argon) was flowing at a rate of about 1.0 cfm.

D. The RF plasma torch would be a better plasma generator for a small experiment to demonstrate MHD principles.

E. A device to demonstrate MHD power conversion principles would require the use of a plasma generator similar to the DC plasma torch.

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PART X.

APPENDIXES

A. Appendix I - Operational Details of the DC Torch

The general procedures for operating the DC plasma torch were given in Part IV, Section A, 2. This appendix has been included for those who would be interested in actually operating a torch such as described, after it had been built. Before the equipment is set up, the water flow through the electrodes should be checked for full pressure and any leaks should be corrected. The movable electrode, the brass rod and tungsten, should be loose enough to move back and forth easily, but tight enough to limit the flow of gas past the joint. The gas inlet tubes are fragile and should be handled with care.

The water cooling system need only be turned on until a full stream of water comes from the drain tube (about 1 gallon/minute). The clamp in the cathode cooling line should be tightened so that about 60-80 per cent of the water is flowing through the anode cooling chamber.

The gas system is simple, but should be checked for leaks. Bottled gas is expensive and should not be wasted. The hoses and pipe used to connect the various pieces of equipment in the gas system should be fairly short since the pressure drop per foot is high for the flows used (about 1 psi/foot). The critical orifice flow meter works very well, but for the range of flows within which the torch was operated (1-7 cfm), two orifice plates were necessary for accurate coverage. It was found worthwhile to calibrate the larger

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orifice (#31) for pressure ranges below 20 psig. After this was done, the meter was usable over the entire range of flows with only one orifice. When operating the torch, it may be desirable to turn the gas back on for a few minutes after extinguishing the arc to aid in cooling the inside of the chamber.

A few comments should be made about the HF control unit. While this unit is on, HF voltage is present across the anode to ground, any ground. The electrodes should be separated as far as possible (about 2 inches) and the starter turned on. Any buzzing should indicate an arc path. Before satisfactory operation was obtained on this torch, two such major arc locations were found. First it was discovered that the torch was arcing over on the outside between the anode cooling water outlet and the stand. The stand was clamped to a metal table and it provided a good ground. The distance involved was about $\frac{1}{4}$ of an inch. The torch would operate only for electrode separation less than that distance. This was finally corrected by moving the stand back from the water outlet about one inch. After the correction, the starter would breakdown the gap for electrode separations greater than $\frac{1}{2}$ inch. The second arcing problem was due to insulation breakdown through the cable supplying power to the anode and the metal table on which the cable laid. Propping the cable up off the table eliminated this problem.

Actual operation of the torch is much as described before. A few words of warning. When first operating the torch, do not look directly at the nozzle as the bright flash of the plasma jet can be blinding. Use a face protector with a strong filter when looking at the jet. Also, before starting, the gas flowing through the nozzle

produces a high whistle, but when the torch starts, the gas velocity increases about 10-15 times and a deafening roar is heard throughout the room.

The torch has time operating limits. At high power levels (20 kw), it should only be run about 30 seconds. At low power levels (less than 5 kw), operating time can be as long as several minutes. The main damage of overheating is in the "Micarta" chamber. The interior chars and the laminated layers begin to peel off. This damage is most noticeable at low gas flows when the cooling provided by the gas is small. A long arc gap will also overheat the chamber.

When shutting the torch down, the cooling water should be left on. This flow of cooling water should not be turned off until the electrodes are cool to the touch. Needless to say, all the power should be turned off (especially the HF control unit) before disassembling the torch to inspect the anode, cathode and interior of the chamber. This final inspection of the electrodes and chamber shows the conditions under which the torch has been operated. With no change in appearance here, the power is well within the operating range. At maximum rated power levels, the cathode will show evidence of arc rotation by swirls of material around the cathode surface. When the torch has been overloaded, the cathode material is sputtered and blow into the nozzle leaving pieces of tungsten in the nozzle. The carbon anode will be severely pitted.

B. Appendix II - Operational Details of the RF Torch

The procedure outlined in Part IV, Section B, 2 for operating the RF plasma torch should be adequate to build operating experience on. The peculiarities of each system can be overcome only by operating it. For this torch the frequencies of interest are from about 4-10 mc. Most industrial RF generators of this range are designed for dielectric heating. This means that the experimenter must adapt the unit to induction heating. The loading units of the generator must be adjusted for adequate power output with an induction load. Some minor circuit changes may be necessary in order for some particular units to operate properly in this fashion.

The gas supply system offered no problems. Once again the correct orifice should be chosen to provide full coverate in the gas flow range of interest (0.1-2 cfm). Calibrating the orifice outside its normal operating range is an aid in experimental procedure.

The coil used is best determined experimentally. Several coils should be used and several sizes were tried. The coil that had the smallest inside diameter and the smallest spacing between turns seemed to work best. The coil wire itself should be large enough so that the coil power losses can be kept small. A pancake coil would probably provide a shorter plasma, with a higher temperature than the long coil. Since the power induced in the plasma is proportional to the magnetic flux, any scheme that increases the flux produces a better plasma jet.

At the low power levels used, the torch would not start itself. A small "testla" coil was used to ionize the gas initially. Once the torch started, it was very quiet in operation. The jet was

not extremely bright and could be viewed directly. No excess heating of the torch itself was noted, but the coil discolored indicating overheating of the copper. At high power levels, care should be exercised so that the glass tube does not soften and droop into the coil.

When turning the torch off, it is only necessary to shut off the RF power generator. The gas supply should be left on for several minutes to provide cooling for the torch. When the torch is cool, the gas should be shut off. The RF torch is extremely simple to operate once the preliminary adjustments have been made on the equipment and the operating parameters set for optimum operation.